Thermoelectric effects in superconductors

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It is widely believed that temperature gradient does not induce electric field in the superconductor and consequently that thermoelectric effects do not exist, or are negligible in these materials. This statement is correct only as far as effective electric field or gradient of the electrochemical potential is concerned. In normal metals temperature gradient generates effective electric field, which nulls out thermally induced diffusion current. In superconductor the diffusion current of quasiparticles is canceled a counterflow of supercurrent. Superconducting current induces the true electric field, which can be approximated by gradient of the screened Bernoulli potential. It explains familiar giant thermomagnetic flux observed in superconducting thermocouples. Contactless measurements of thermoelectric effects are suggested.

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I. Introduction

In the normal metal temperature gradient induces electric field, which nulls out thermally induced diffusion current. If two different metals are connected together so that they form a closed loop thermocouple, temperature gradient induces circulating thermocurrent. In superconductors the diffusion current of quasiparticles $j_n = -L_T \nabla T$ is canceled by a counterflow of supercurrent. Measured thermoelectric voltage is zero or negligibly small what is the base for widely spread opinion, that thermoelectric effects do not exist in superconductors. Nevertheless, it was experimentally proved that in the superconducting thermocouple temperature gradient induces giant flux [1], proportional to the transport coefficient L_T measured above T_c. The question is: what is the origin of the current which evocates the emerging flux?

II. The true and the effective electric field

The answer to this question is based on a simple notion. The true electric field properly used in Maxwell equations must be distinguished from the effective electric field defined as a gradient of electrochemical potential. At equilibrium the electrochemical potential is constant and it implies that gradient of the electrochemical potential, often refferred to as the effective electric field, is zero. Voltmeter measures difference of the electrochemical potential between the two contacts and by a lot of measurements the zero (effective) electric field in superconductor

was unambiguously proved. But it does not say much about the true electric field. Already in the very early theories it was predicted (see e.g. [2]), that superconducting current generates perpendicular (true) electric field. The prediction was experimentally verified. By a contactless capacitive pickup the presence of nonzero (true) Hall voltage in the superconductor in Meissner state was proved (see e.g. [3]). From the measurements, from the BCS theory [4] and also from the Ginzburg-Landau theory [5, 6] it follows, that the true electric field can be approximated by the gradient of the screened Bernoulli potential

$$e\varphi \approx n_s/n\left(-\frac{1}{2}m\mathbf{v}_s^2\right), \tag{1}$$

where $\mathbf{v}_s$ denotes velocity of the superconducting particles, n_s and m their density and mass.

III. Thermoelectric effects in superconductors

In superconductors the effective electric field generated by the temperature gradient is zero, or negligibly small. Here we show that the true electric field induced by the temperature gradient is relevant. Let us imagine a single superconducting slab $-d < x < d$ in external magnetic field B_0, directed parallel to the z axis. Superconductor in Meissner state exponentially screens magnetic field, so that $B = B_0\cosh(x/\lambda)/\cosh(d/\lambda)$. If temperature and consequently also the London penetration depth $\lambda = \sqrt{m/\mu_0 n_s(T)e^2}$ increases along the y axis, from Maxwell equation $\mu_0\mathbf{j} = \nabla\times\mathbf{B} = [\partial_y B, -\partial_x B, 0]$ follows that screening current has nonzero component also in the x direction. The trajectories of superconducting particles are schematically sketched on Fig.1.

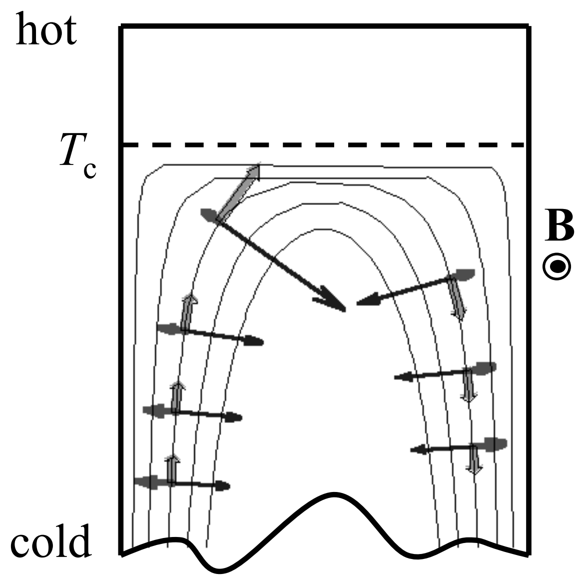

FIG. 1. Schematic picture of the screening current in a superconducting slab with temperature gradient.

On the cold end (foot of the picture) the penetration depth is small and screening current is concentrated close to the surface. On the side where screening current flows in the direction of increasing temperature (left hand side on the picture), the velocity of the Cooper pairs (marked by double arrows) increases, near T_c changes direction and returns back on the other side. Lorentz and electric field forces marked by thin and thick arrows, respectively, are perpendicular to the velocity of superconducting particles. Note, that the electric field force does not fully compensate the Lorentz force. The balance of forces is assured by the superconducting-normal state fluid (s-n) interaction, in the literature often called quasiparticle screening [7].

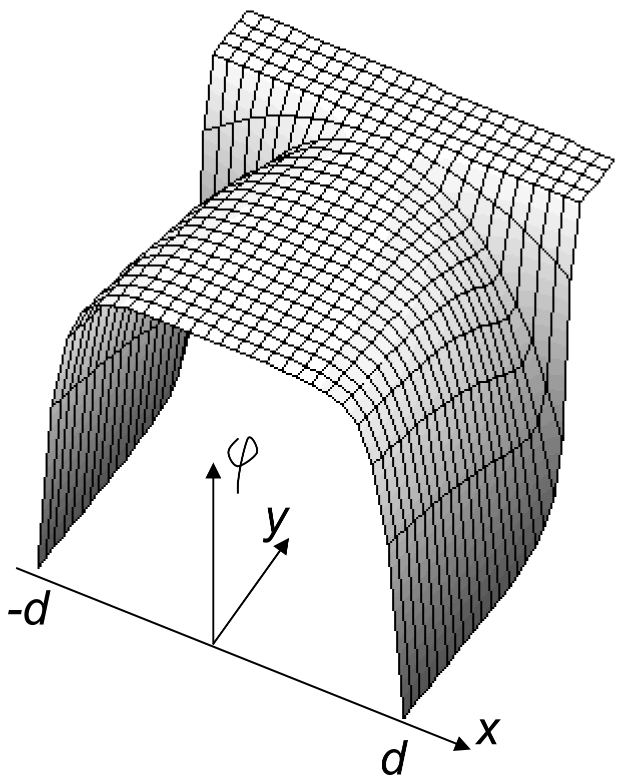

FIG. 2. Screened Bernoulli potential in superconductor. At position where temperature reaches T_c a sharp, but continuous step is present.

The scalar potential in the screened Bernoulli approximation is sketched in the figure 2. Let us note that as expected, the sharp step at position where temperature reaches T_c is continuous - in the limit $t \to 1$ the scalar potential $\varphi \to 0$. We must stress, that presented drawing displays scalar potential, which is not measurable by standard voltmeter measurement with contacts, but which should be observable by contactless measurements.

IV. Summary

In ref. [8] it was showed, that taking into account the electrostatic potential it is possible to treat thermoelectric properties in superconductors on the same footing as in the normal metals. From the scalar potential matching thermally induced magnetic flux in agreement with experiment was found. Nevertheless, one open question remained. In the cited paper we have matched Bernoulli potential only at the inner surface of the thermocouple. By showing here the distribution of the scalar potential in the close vicinity of T_c, brought arguments indicating, that the solution has the desired properties in the whole cross-section. Last but not least, we would like to encourage contactless measurement of the thermoelectric effects in superconductors.

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